Antenna Switching Circuit

This invention relates to a switching circuit for use at the antenna of a multiband mobile cellular handset to select
5 between the TX and RX modes of the bands.

Multiband GSM-based mobile cellular handsets generally include a number of circuits for the TX and RX of the different bands of the handset. To select between the TX and RX modes of the
10 various RF bands, a switching circuit is usually employed at the antenna of the handset. The function of the switching circuit is to electrically connect the antenna of the cellular handset to the TX or RX circuit of the band which is in use at a given time, and to simultaneously isolate all other sections
15 of the handset from the antenna. This switching circuit is often incorporated into a single module, and this switching module is sometimes referred to as an antenna switch module (ASM). In addition to the switching function described above, the ASM may include low pass filters at the TX ports to filter
20 out unwanted harmonics from the TX signals.

A dual band cellular handset is normally designed to operate on a low band and on a high band. For example, handsets designed to operate within Europe generally are capable of
25 transmitting and receiving on the EGSM and DCS bands. The frequencies of operation of the TX and RX of the EGSM and DCS bands are listed in Table 1. It can be seen that the TX and RX frequencies of the EGSM band are centred around 920 MHz (low band), whereas the TX and RX frequencies of the DCS band
30 are centred around 1800 MHz (high band). A dual band ASM, for use in such a dual band cellular handset, facilitates switching of a single antenna between a TX low band input, a TX high band input, an RX low band output and an RX high band output. Consequently, a conventional dual band ASM has 5

ports: TX low band port, TX high band port, RX low band port,
RX high band port, and antenna port.

Cellular System	TX Frequency Range	RX Frequency Range
AGSM	824-849 MHz	869-894 MHz
EGSM	880-915 MHz	925-960 MHz
DCS	1710-1785 MHz	1805-1880 MHz
PCS	1850-1910 MHz	1930-1990 MHz
W-CDMA	1920-1980 MHz	2110-2170 MHz

5   Table 1.

European Patent Application EP 0 921 642 discloses a
conventional dual band ASM employing a diplexer at the antenna
to separate the low band and the high band and further
10   employing a pair of SP2T PIN switches to select between the TX
and RX in each band. The ASM described in EP 0 921 642 also
includes low pass filters at each of the two TX inputs.

It is an object of this invention to provide an improved
15   antenna switching circuit which avoids the need for a diplexer
at the antenna to separate the low band and the high band.

This object is met by the invention described by claim 1.

20   An embodiment of the invention provides a dual band ASM which
represents a significant departure from the conventional
topologies of dual band PIN switched ASMs as exemplified by
EP 0 921 642. The embodiment has only 4 ports: TX low band
port, TX high band port, RX port, and antenna port. It is
25   based around a dual band SP3T PIN switch which can alternately
connect the antenna port to the TX low band port, the TX high
band port or the RX port. The various switching states are
implemented using two control voltages.

The absence of a diplexer in the TX and RX signal paths results in a significant reduction in the insertion loss of the ASM. In addition, this absence improves the VSWR (Voltage

5   Standing Wave Ratio) at the various ports of the ASM.

The embodiment can be modified so that there are a pair of RX ports for cellular handset applications requiring an ASM with a low band RX port and a high band RX port. This modification

10   can be achieved by the inclusion of a conventional diplexer at the RX output. In this case the benefits of reduced loss, and reduced VSWR, apply to the TX ports only.

The TX high band frequency range, i.e. the frequency range of

15   signals entering the TX high band port, may be that of a single cellular high frequency band, e.g. the DCS band, or that of a combination of cellular high frequency bands, e.g. the DCS and PCS bands. Similarly, the TX low band frequency range, i.e. the frequency range of signals entering the TX low

20   band port, may be that of a single cellular low frequency band, e.g. the EGSM band, or that of a combination of cellular low frequency bands, e.g. the EGSM and AGSM bands.

Embodiments of the invention will now be described, by way of

25   example, with reference to the accompanying drawings, in which:

Fig. 1 shows a circuit diagram of an ASM according to an embodiment of the invention employing a SP3T silicon PIN diode

30   switch.

Fig. 2 shows a modified version the ASM of fig. 1, where low pass filters have been added at each of the TX inputs.

Fig. 3 shows the ASM of fig. 1 modified to include a pair of RX ports.

Fig. 4 shows a modification of the ASM of fig. 1 where each of the phase shifting transmission lines T_1 and T_2 have been replaced by a phase shifting network comprising of lumped components M_1 and M_2.

Fig. 5 shows a dual band front end module (FEM) based on the ASM of fig. 1.

Fig. 6a shows a block diagram of a SAW triplexer.

Fig. 6b shows a circuit diagram of a possible implementation of the SAW triplexer of fig. 6a.

Fig. 7 shows a conventional diplexer.

Fig. 8 shows a low-band, high-band branching circuit which can be used in the impedance matching circuit of the SAW triplexer of fig. 6a.

Fig. 9 shows a circuit diagram of a PIN switched triple band FEM, based on the ASM of fig. 1 and the triplexer of fig. 6a.

Fig. 10a shows a block diagram of a SAW quadplexer.

Fig. 10b shows a possible implementation of the SAW quadplexer of fig. 10a.

Fig. 11 shows a circuit diagram of a quadband FEM, based on the ASM of fig. 1 and the quadplexer of fig. 10a.

Detailed description of the invention

Fig. 1 shows a block diagram of an ASM which employs a SP3T switch, comprising four silicon PIN diodes D_1 to D_4, to selectively connect an antenna port 10 to a TX high band input port 12, a TX low band input port 14, or an RX output port 16 according to the combination of voltages VC1, VC2 applied at voltage input terminals 18, 20 respectively.

The TX high band port 12 is connected via a DC blocking capacitor C_B to the anode of D_2, and the TX low band port 14 is similarly connected via a DC blocking capacitor C_B to the anode of D_1. The antenna port 10 is connected at node A to the cathodes of both diodes D_1 and D_2, at node B to the anode of D_3 via a first microstrip transmission line T_1, and at node C to the anode of D_4 and the RX output port 16 via a further microstrip transmission line T_2 connected in series with the first transmission line T_1. The cathode of D_3 is connected to ground via an LC resonator comprising L_1 and C_1, and the cathode of D_4 is likewise connected to ground via an LC resonator comprising L_2 and C_2. The inductances L_1 and L_2 may be specifically selected to optimise the electrical characteristics of the antenna switch, or may be constituted solely by the parasitic inductances of the respective diodes D_3, D_4.

The voltage input terminal 18 for VC1 is connected via a current regulating resistor R_I and a DC choke L_C to the anode of D_1, and via a further DC choke L_C to the cathode of D_3. A voltage smoothing capacitor C_S is added to the circuit, in a configuration such that one terminal of this capacitor is connected to the node where the resistor R_I and the two DC chokes L_C meet, and the other terminal is connected to ground.

The voltage input terminal 20 for VC2 is similarly connected
via a current regulating resistor R_I and a DC choke L_c to the
anode of D_2, and via a further DC choke L_c to the cathode of
5   D_4. A second smoothing capacitor C_s is added to the circuit,
so that one terminal of this second capacitor is connected to
the node where the resistor R_I and the two DC chokes L_c meet,
and the other terminal is connected to ground.

10   The TX low band of fig. 1 could be defined by the upper and
lower edges of the frequencies of the AGSM cellular system,
the EGSM cellular system, or any other cellular system with a
frequency range around 1GHz, or any combination of these
systems (see Table 1). The TX high band could be defined by
15   the upper and lower bounds of the frequencies of the DCS
cellular system, the PCS cellular system, or any other
cellular system with a frequency range around 2GHz, or any
combination of these systems (see also Table 1).

20   In the present embodiment it is assumed that the TX low band
is defined by the TX frequency range of the EGSM cellular
system, and that the TX high band is defined by the TX
frequency range of the DCS cellular system.

25   The ASM circuit of fig. 1 has three switching states (to allow
SP3T operation). The switching logic for all three states is
given in Table 2.

Switching State	ASM Function	VC1	VC2
1	RX	0	0
2	High Band TX	0	+V
3	Low Band TX	+V	0

Table 2.

30

Switching state 1.

In this state the voltages VC1 applied at 18 and VC2 applied
at 20 are both zero. This results in a potential difference
of zero volts across all four diodes D_1-D_4, so that all diodes
are in the off state. A diode in the off state has a very
high impedance, hence, in this state, the two TX ports 12 and
14 are isolated from the circuit, and the two resonators (one
comprising L_1 and C_1 and the other comprising L_2 and C_2) leading
to ground from nodes B and C are also isolated from the
circuit.

Consequently, in switching state 1, a signal entering the ASM
of fig. 1 at the antenna port 10 will pass from the antenna
port 10 to node A, and from node A, along transmission lines T_1
and T_2, to the RX output port 16.

Switching State 2

In this state, the voltage VC2 applied at 20 is high and the
voltage VC1 applied at 18 is zero, so that diodes D_1 and D_4 are
in the off state and diodes D_2 and D_3 are in the on state. A
diode in the on state has a very low impedance, hence, in this
state, the TX high band port 12 is connected directly to node
A via the very low impedance of the switched on diode D_2.
Conversely, since diode D_1 is switched off, the impedance of
the circuit path from node A to the TX low band port 14 is
very high, and hence the TX low band port is isolated from
node A. Along the circuit path from node A to the RX port 16,
diode D_3 is switched on, connecting node B to ground via the
series LC resonator comprising L_1 and C_1. This resonator is
tuned to have a resonance at the centre of the high band TX
frequency range (1747.5MHz for DCS), and therefore within the

range of the DCS TX frequencies the impedance to ground at
node B is almost zero (i.e. a short circuit). The short
circuit at node B is connected to one end of the transmission
line T_1, the other end of the line T_1 being connected to node

5   A. Transmission line T_1 is constructed to have an electrical
length of 90 degrees at the centre of the high band TX
frequency range (1747.5MHz). A transmission line with an
electrical length of 90 degrees at a particular frequency is
often referred to as a quarter wave transmission line, and the

10   phase of the reflection coefficient at one end of a quarter
wave transmission line is rotated through π radians at the
other end. For example, a short circuit, which has a
reflection co-efficient of -1, will have a reflection co-
efficient of +1 when measured from the far end of a quarter

15   wave transmission line and conversely, an open circuit, which
has a reflection co-efficient of +1, will have a reflection
co-efficient of -1 when measured from the far end of a quarter
wave transmission line. Hence, at frequencies near 1747.5MHz
the short circuit at node B (which has a reflection co-

20   efficient of -1) appears like an open circuit at node A (which
has a reflection co-efficient of +1), so that at these
frequencies the path from node A to the RX port 16 is
electrically equivalent to an open circuit.

25   To summarise, in switching state 2, the branch of the ASM
circuit leading from node A to the high band input 12 has a
very low impedance, whereas two of the branches connected to
node A are open circuit (or have a very high impedance): the
branch leading to the RX port 16 and the branch leading to the

30   TX low band port 14. Consequently, signals in the range 1710-
1785 MHz coming from the TX high band port 12 will pass via
diode D_2 and node A to the antenna port 10.

Switching State 3

In this state, the voltage VC1 applied at 18 is high and the
voltage VC2 applied at 20 is zero, so that diodes D_2 and D_3 are

5 in the off state and diodes D_1 and D_4 are in the on state.
Since diode D_2 is switched off, the impedance of the circuit
path from node A to the TX high band port 14 is very high, and
hence the TX high band port is isolated from node A. However
the TX low band port 14 is connected directly to node A via

10 the very low impedance of the switched-on diode D_1. Along the
circuit path from node A to the RX port 16, since diode D_3 is
in the off state, the resonator, comprising L_1 and C_1, which
connects diode D_3 to ground is isolated from node B. However,
diode D_4 is switched on, so node C is connected to ground via

15 the LC resonator comprising L_2 and C_2. This resonator is tuned
to have a resonance at the centre of the low band TX frequency
range (897.5MHz), and therefore near this frequency, the
impedance to ground at node C is almost zero (i.e. a short
circuit). The short circuit at node C is at one end of the

20 pair of transmission lines T_1 and T_2 which are connected in
series. Since diode D_3 is switched off in this state, the pair
of transmission lines T_1 and T_2 can be treated like a single
transmission line, with an electrical length which is equal to
the sum of the lengths of both lines. As stated above, T_1 is

25 constructed so that it has an electrical length of 90 degrees
at the centre of the high band TX frequency range (1747.5MHz);
this corresponds to an electrical length of approximately 46
degrees at the centre of the low band frequency range
(897.5MHz). Accordingly, T_2 is designed so that it has an

30 electrical length of approximately 44 degrees at the centre of
the low band frequency range (i.e. so that the transmission
lines T_1 and T_2 have a combined electrical length of 90 degrees
at 897.5MHz). The other end of this pair of transmission
lines is connected to node A. As described above, a

transmission line with an electrical length of 90 degrees has the effect of rotating the phase of the reflection coefficient at one end of the line through π radians at the other end. Hence, at frequencies around 897.5MHz the short circuit at

5   node C appears like an open circuit at node A, so that at these frequencies, the path from node A to the RX port 16 is electrically equivalent to an open circuit.

To summarise, in switching state 3, the branch of the ASM

10   circuit leading from node A to the low band input 14 has a very low impedance, whereas two of the branches connected to node A are open circuit (or have a very high impedance): the branch leading to the RX port 16 and the branch leading to the TX high band port 14. Consequently, signals in the range 880-

15   915 MHz coming from the TX low band port 14 will pass via diode D_1 and node A to the antenna port 10.

The primary difference between the conventional ASM disclosed in EP 0 921 642 and the novel ASM of fig. 1 is that the

20   conventional ASM is divided into a low band section and a high band section by placing a diplexer at the antenna. The absence of a conventional diplexer at the antenna of the ASM of fig. 1 reduces the insertion loss of the ASM. The reduction in insertion loss is due to the fact that there are

25   less components in the paths of TX and RX signals which enter the ASM. The insertion loss of a conventional diplexer is typically in the order of 0.5dB at the low band and 0.75dB at the high band. The absence of a diplexer at the antenna port also considerably improves the VSWR of the ASM, which is of

30   paramount importance in the TX path, since a high VSWR results in a large signal being reflected back into the power amplifier of the handset which has a detrimental effect on the RF performance of the cellular handset.

Another difference between the ASM of fig. 1 and the
conventional ASM of EP 0 921 642 is that there is only a
single RX port for the ASM of fig. 1, whereas the ASM of
EP 0 921 642 has two RX ports - low band RX and high band RX.

5

Fig. 2 shows the novel ASM of fig. 1 modified to include low
pass filters at the TX low band input and at the TX high band
input, which may be required to filter out unwanted harmonics
present in the TX signals entering the TX ports of the ASM.

10

For applications where a pair of RX ports are required, the
ASM of fig. 1 can be modified to suit the requirements by the
inclusion of a conventional diplexer at node C, as shown in
fig. 3.   Inclusion of a diplexer at the RX port 16 of the ASM
15   of fig. 1   provides RX low and RX high band ports 16', 16"
respectively.   Although this modification increases the
insertion loss of the ASM along the RX paths, it has no effect
on the insertion loss of the ASM along the TX paths.
Similarly, this modification has no effect on the VSWR at the
20   TX ports and at the antenna port when the ASM is in either of
the TX modes.   Consequently, it can be seen that the ASM of
fig. 1 can be configured to give exactly the same
functionality as the conventional ASM of EP 0 921 642, but
with the additional benefit of lower insertion loss in the TX
25   paths and improved VSWR in the TX paths.

It has been stated herein that in switching state 2, the
purpose of the transmission line T_1 in figs. 1-3 is to
transform the short circuit at node B, which results from the
30   switched on diode D_3 connected in series with L_1 and C_1, so
that this short circuit appears as an open circuit at node A.
Similarly it has been stated that the purpose of the
transmission line T_2 is so that the combined effect of T_1 and
T_2 is to transform the short circuit at node C, resulting from

the switched on diode D_4 connected in series with L_2 and C_2, so
that this short circuit appears as an open circuit at node A.

Accordingly, the transmission lines T_1 and T_2 can individually
5   be replaced by any electrical circuit which has the effect of
adding the appropriate phase shift at the TX low band, and the
appropriate phase shift at the TX high band.

Fig 4 shows a modification of the ASM of fig. 1, where the
10 phase shifting transmission lines T_1 and T_2, have been replaced
with circuits M_1 and M_2 each comprising a respective pi-type LC
network which includes a single series inductor buffered on
either side by a shunt capacitor. The inductor and capacitors
in the circuit M_1 are chosen so that M_1 gives rise to the same
15 electrical phase shift as transmission line T_1; whereas the
inductor and capacitors in the circuit M_2 are chosen so that
the circuits M_1 and M_2 together give rise to the same
electrical phase shift as the serially connected transmission
lines T_1 and T_2.
20

Typically, all passive components such as transmission lines,
matching circuits, and LC elements required to implement
embodiments of the invention are implemented within and/or on
the surface of a multi-layer substrate such a Low Temperature
25 Co-Fired Ceramic (LTCC) substrate.

Application to Dual Band Front End Module

A front end module (FEM) is an ASM which includes the RX
30 filters that are normally located external to the ASM. The RX
filters employed are usually of the surface acoustic wave
(SAW) type due to their small size and low insertion loss.
SAW filters have the additional benefit of being capable of
providing unbalanced to balanced conversion, which is useful

in cases where the RX input of the cellular handset comprises
a pair of balanced terminals. The ASM of fig. 2 can be
converted into a dual band FEM by the addition of a pair of RX
SAW filters 24 and 26 at the outputs 16', 16'' of the diplexer
5   22 as depicted in fig. 5.

Application to Triple Band Front End Module

In recent times, there has been an increasing demand for
10   triple band cellular handsets, which can operate on the EGSM,
DCS and PCS bands (Table 1).

For triple band FEM, two TX ports are usually sufficient, as
it is common for triple band cellular handsets to include only
15   two power amplifiers, one for the EGSM TX, and one for the DCS
and PCS TX. However separate RX ports are usually required
for each band. So a triple band FEM generally includes 6
ports: TX low band port, TX high band port, three separate RX
ports, and an antenna port.
20

An FEM covering the EGSM, DCS and PCS bands can be constructed
from a conventional dual-band ASM as follows: by adjusting the
TX high band section of the ASM so that it is optimised for TX
signals in a range extending from the lower edge of the DCS TX
25   and the upper edge of the PCS TX band (i.e. 1710 to 1910MHz);
by the addition of a single EGSM SAW filter at the low band RX
output; and by the addition of a DCS/PCS SAW duplexer at the
high band RX output – see US Patent Application
US2002/0032038.
30

To construct an FEM covering the EGSM, DCS and PCS bands using
the ASM of fig. 1, the TX section of the ASM of fig. 1 must be
adjusted as follows: the transmission line T_1 is adjusted so
that it has an electrical length of 90 degrees for signals

midway between the lower edge of the DCS TX and the upper edge
of the PCS TX band (i.e. 1810MHz); transmission line T_2 is re-
adjusted so that the combined electrical length of T_1 and T_2 is
90 degrees for signals in the centre of the EGSM TX band

5   (897.5MHz); the LC resonator comprising L_1 and C_1 is adjusted
so that its resonant frequency is equal to 1810MHz.

Similarly the RX section of the ASM of fig. 1 must be modified
to include three bandpass filters, one for each of the EGSM,

10   DCS and PCS bands. However, the ASM shown in fig. 1 has only
a single RX port, so the method outlined in US Patent
Application US2002/0032038 cannot be used here.

To convert the RX section of the ASM of fig. 1 for triple band

15   FEM functionality, a circuit is required which has a single
input, which includes three outputs, and which further
includes three RX bandpass filters such that the outputs of
each of the three bandpass filters are connected to the
outputs of the said circuit. This circuit must further be

20   designed so that electrical signals at frequencies within the
pass bands of any one of the bandpass filters which are
applied to the input of the circuit will pass directly to the
corresponding output of the circuit. Preferably the three
bandpass filters are SAW filters and in such case this circuit

25   will be referred to as a SAW triplexer herein.

A block diagram of a SAW triplexer is shown in fig. 6a,
wherein three balanced output SAW filters 30, 32 and 34 are
connected to node C via an impedance matching circuit 36 to

30   provide three RX ports 16A, 16B and 16C with balanced outputs,
one for each band. The impedance matching circuit 36 is
designed so that when the three balanced outputs of the SAW
triplexer are optimally terminated, the impedance to ground
from node C along the circuit paths through any two of the SAW

filters 30-34 is very high compared with the impedance to
ground along the circuit path through the other SAW filter at
frequencies within the passband of that filter.

5   A possible implementation of the SAW triplexer of fig. 6a is
shown in fig. 6b. This circuit includes a primary impedance
matching sub-circuit 38 which is connected to node C, and a
secondary impedance matching sub-circuit 40 which is connected
to node D. The circuit also includes the three balanced
10   output bandpass SAW filters: one SAW filter 30 with a pass
band which coincides with the EGSM cellular system, one SAW
filter 32 with a pass band which coincides with the DCS
cellular system, and one SAW filter 34 with a pass band which
coincides with the PCS cellular system.
15

The function of the primary sub-circuit 38 (an example of
which will be described below) is the isolation of the high
band SAW filters from node C at low band frequencies, and the
simultaneous isolation of the low band SAW filter from node C
20   at frequencies in the high band.

The secondary sub-circuit 40 comprises a length of
transmission line T_3 connected to the input of the PCS SAW
filter 34, and an LC network 42 connected to the input of the
25   DCS SAW filter 32. The length of line T_3 at the input of the
PCS filter 34 has the effect of raising the impedance of the
path from node D to the PCS output to a very high value at
frequencies within the DCS band. However, the transmission
line T_3 has no effect on the response of the PCS filter at
30   frequencies within the PCS band. Similarly, the LC network 42
at the input of the DCS filter 32 has the effect of raising
the impedance of the path from node D to the DCS output to a
very high value at frequencies within the PCS band, but has no
effect on the response of the DCS filter within the DCS band.

Thus it can be seen that the secondary sub-circuit 40, which
is connected to node D, together with the DCS and PCS SAW
filters 32 and 34, achieves the functionality of a duplexer,
so that electrical signals at frequencies within the DCS pass
5   band at node D will pass directly to the DCS output of the
triplexer, and electrical signals at frequencies within the
PCS pass band at node D will pass directly to the PCS output
of the triplexer.

10   A number of other embodiments of the secondary sub-circuit 40
exist in order that the secondary sub-circuit 40 together with
the SAW filters 32 and 34 achieve the functionality of a DCS /
PCS duplexer. A second embodiment would involve replacing
transmission line T_3 with a matching circuit comprising of
15   discrete components in the same manner that the transmission
lines T_1 and T_2 in figs 1-3 can be replaced by LC matching
circuits M_1 and M_2 as shown in fig. 4 above. A third
embodiment would involve replacing the LC network 42 with a
further transmission line, though for this embodiment, the new
20   transmission line would preferably be connected in parallel
with filter 42, so that one end of the transmission line was
connected directly to ground.

The primary impedance matching sub-circuit 38, which is
25   connected to node C of the SAW triplexer of fig. 6b can be
implemented by a conventional diplexer such as that shown in
fig. 7. A conventional diplexer includes three ports: a low
band port, which is connected to one side of the circuit; a
high band port, which is connected to the other side of the
30   circuit; and a third port, which is connected to a point
inside the circuit (denoted by node C in fig. 7). The
component values of the diplexer are chosen so that when all
of the ports of the diplexer are optimally terminated, the
response of the diplexer, measured from node C to the low band

port is that of a low pass filter, and the response of the
diplexer, measured from node C to the high band port is that
of a high pass filter. Hence, the use of a conventional
diplexer, such as that shown in fig. 7, for the primary sub-
5 circuit 38 in the SAW triplexer of fig. 6b, achieves the
desired result i.e. the isolation of the high band SAW filters
from node C at low band frequencies, and the simultaneous
isolation of the low band SAW filter from node C at
frequencies in the high band.
10

Despite fulfilling the isolation requirements of the primary
sub-circuit 38 of fig. 6b, the filtering effects introduced by
a conventional diplexer are not a necessary requirement of the
primary sub-circuit 38.
15

Fig. 8 shows an alternative circuit for the primary
sub-circuit 38 of fig. 6b, which may be used in place of the
conventional diplexer to isolate the high band and low band
SAW filters. The circuit of fig. 8 is a branching circuit
20 which comprises a pair of tuned circuits: a parallel tuned
circuit 44, comprising L_P and C_P, and a series tuned circuit
46, comprising L_S and C_S. These tuned circuits are connected
together at node C. The values of the inductance and
capacitance in the parallel tuned circuit 44 are chosen so
25 that together with the input impedance of the optimally
terminated low band SAW filter 30 they form a resonant circuit
with a resonant frequency which is midway between the lower
edge of the DCS RX band and the upper edge of the PCS RX band
(i.e. 1897.5MHz). Similarly the values of the inductance and
30 the capacitance in the series tuned circuit 46 are chosen so
that together with the input impedance of the secondary sub-
circuit 40, and the optimally terminated high band SAW filters
32 and 34, they form a series resonant circuit with a resonant

frequency which is midway between the lower edge of the DCS RX band and the upper edge of the PCS RX band. For optimum isolation, the inductances and capacitances in both resonant circuits are chosen so that the Q of the parallel resonant circuit is equal to the Q of the series resonant circuit.

For the branching circuit of fig. 8, the values of the inductances and capacitances are calculated using equations 1a and 1b:

$$L_S = \frac{QZ}{\omega_{HB}} \qquad\qquad C_S = \frac{1}{\omega_{HB}QZ} \qquad\qquad \textit{Equation 1a}$$

$$L_P = \frac{Z}{\omega_{HB}Q} \qquad\qquad C_P = \frac{Q}{\omega_{HB}Z} \qquad\qquad \textit{Equation 1b}$$

where Z is the input impedance of the optimally terminated SAW filters within their respective pass bands, ω_{HB} is the frequency midway between the lower edge of the DCS RX band and the upper edge of the PCS RX band, and Q is the quality factor of the series and parallel resonators. For best results the Q in equations 1a and 1b should be in the range of 1 to 2.

The circuit of fig. 8 has the benefit of reduced complexity compared with the conventional diplexer of fig. 7. The circuit of fig. 8 additionally requires no connections to ground, thereby eliminating the need for via holes in the substrate of the triplexer, which would normally be required if the first sub-circuit 38 comprised a conventional diplexer such as that depicted in fig. 7.

It should be noted that the description of the triplexer described above is based on a circuit which employs three balanced output SAW filters. However, the triplexer could

employ three unbalanced output SAW filters, and one or more of the SAW filters could be replaced by another type of RF filter, such as a dielectric resonator filter; a film bulk acoustic resonator filter, such as that described in US

5   patents US6462631 or US6215375; or a multi-layer filter implemented by discrete inductors and capacitors fabricated in an LTCC substrate.

A triple band FEM for the EGSM, DCS and PCS bands, implemented

10   using the SAW triplexer of fig. 6a and the ASM of fig. 1 is shown in fig. 9. Dividing the FEM into two separate structures (an ASM and a SAW triplexer) enables a modular design approach, because the two structures are substantially independent of each other.

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Application to Quad Band Front End Module

A further option for multi-band GSM-based mobile cellular handsets is that the handset be capable of transmitting and

20   receiving on any one of four bands. For example, a quad band handset could be designed to operate on the AGSM, EGSM, DCS and PCS bands (Table 1).

A quad band FEM can be realised using the SP3T switching

25   circuit of fig. 1, in a similar fashion to the method outlined above for constructing a triple band FEM using the ASM of fig. 1.

As with the triple band FEM described above, a quad band FEM

30   covering the AGSM, EGSM, DCS and PCS bands requires only two TX inputs for the four bands - low band and high band. In this case, the low band TX input is optimised for frequencies ranging from the lower edge of the AGSM TX band to the upper edge of the EGSM TX band, and the high band TX input is

optimised for frequencies ranging from the lower edge of the
DCS TX band to the upper edge of the PCS TX band.

To convert the RX section of the ASM of fig. 1 for quad band
5   FEM functionality, a circuit is required which has a single
input, which includes four outputs, and which further includes
four RX bandpass filters such that the outputs of each of the
four bandpass filters are connected to the outputs of the said
circuit. This circuit must further be designed so that
10 electrical signals at frequencies within the pass bands of any
one of the four bandpass filters which are applied to the
input of the circuit will pass directly to the corresponding
output of the circuit. Preferably the four bandpass filters
are SAW filters and in such case this circuit will be referred
15 to as a SAW quadplexer herein.

A block diagram of a SAW quadplexer is shown in fig. 10a,
wherein four balanced output SAW filters 52, 54 56 and 58 are
connected to node C via an impedance matching circuit 50 to
20 provide four RX ports 16A, 16B, 16C and 16D with balanced
outputs, one for each band. The impedance matching circuit 50
is designed so that when the four balanced outputs of the SAW
quadplexer are optimally terminated, the impedance to ground
from node C along the circuit paths through any three of the
25 SAW filters 52-58 is very high compared with the impedance to
ground along the circuit path through the other SAW filter at
frequencies within the passband of that filter.

A possible implementation of the quadplexer of fig. 10a is
30 shown in fig. 10b. This circuit comprises a primary impedance
matching sub-circuit 58 and a pair of secondary impedance
matching sub-circuits 60 and 62. The function of the primary
impedance matching circuit 58 is the blocking of the high band
SAW filters from node C at low band frequencies, and the

simultaneous blocking of the low band SAW filter from node C
at frequencies in the high band. As with the SAW triplexer of
fig. 6a and 6b, the primary impedance matching circuit 58
could be constituted by a conventional diplexer, such as that
5 of fig. 7, or a branching circuit such as that of fig. 8.
Since the two high band SAW filters 56 and 58 of fig. 10b have
the same passbands of the high band SAW filters 32 and 34 of
fig. 6b, the second impedance matching circuit 60 of fig. 10b
could be realised by an identical circuit to that of the
10 secondary impedance matching circuit 40 of fig. 6b - i.e. a
DCS/PCS SAW duplexer. Similarly, the secondary impedance
matching circuit 62 of fig. 10b is designed so that together
with the low band SAW filters 52 and 54, it constitutes an
AGSM/EGSM SAW duplexer.
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A quad band FEM, implemented using the SAW quadplexer of
fig. 10a and the dual-band SP3T ASM of fig. 1, is shown in
fig. 11. As above, the quad band FEM of fig. 11 comprises two
separate circuits, an ASM and a SAW quadplexer. This
20 structure facilitates a modular design approach, as the two
structures are substantially independent of each other.

This specification has described a novel ASM, which is based
around a dual band SP3T PIN diode switch, and which has 4
25 ports: an antenna port, a TX low band port, a TX high band
port and an RX port. This ASM does not require a diplexer to
separate the TX low band and TX high bands. It can be used in
a dual band cellular handset to connect an antenna to a TX low
band output, a TX high band output, and an RX input. The
30 disclosed ASM has lower insertion loss than a conventional
ASM, and the VSWR is also lower.

The ASM presented here can be configured to offer the same
functionality of a conventional 5 port dual band ASM, by the

inclusion of a diplexer at the RX port. This configuration offers the benefit of lower insertion loss, and improved VSWR in both TX modes compared with a conventional dual band ASM.

5 This specification has further described a SAW triplexer circuit, which has a single input and three separate outputs and which can be used to direct electrical signals which fall within the pass band of any one of the SAW filters from the single input to the output of the relevant SAW filter. This
10 specification has furthermore described a front end module (FEM) which is constructed using the above dual band SP3T ASM and the above SAW triplexer. The FEM constructed in this fashion has very low insertion loss in both TX modes, in addition, the VSWR of this FEM is also very low in both TX
15 modes.

This specification has further described a SAW quadplexer circuit, which has a single input and four separate outputs and which can be used to direct electrical signals which fall
20 within the pass band of any one of the four SAW filters from the single input to the output of the relevant SAW filter. This specification has furthermore described a front end module (FEM) which is constructed using the above dual band SP3T ASM and the above SAW quadplexer. The quad band FEM
25 constructed in this fashion has very low insertion loss in both TX modes, in addition, the VSWR of this FEM is also very low in both TX modes.

The invention is not limited to the embodiments described
30 herein which may be modified or varied without departing from the scope of the invention.